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An exploratory study of lead recovery in lead-acid battery lifecycle in US market: An evidence-based approach

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ABSTRACT

Background: This research examines lead recovery and recycling in lead-acid batteries (LAB) which account for 88% of US lead consumption. We explore strategies to maximize lead recovery and recycling in the LAB lifecycle. Currently, there is limited information on recycling rates for LAB in the published literature and is derived from a single source. Therefore, its recycling efforts in the US has been unclear so as to determine the maximum opportunities for metal recovery and recycling in the face of significant demands for LAB particularly in the auto industry.

Objectives: The research utilizes an evidence-based approach to: (1) determine recycling rates for lead recovery in the LAB product lifecycle for the US market; and (2) quantify and identify opportunities where lead recovery and recycling can be improved.

Methods: A comprehensive electronic search of the published literature was conducted to gather information on different LAB recycling models and actual data used to calculate recycling rates based on product lifecycle for the US market to identify strategies for increasing lead recovery and recycling.

Results: The electronic search yielded five models for calculating LAB recycling rates. The description of evidence was documented for each model. Furthermore, an integrated model was developed to identify and quantify the maximum opportunities for lead recovery and recycling. Results showed that recycling rates declined during the period spanning from 1999 to 2006. Opportunities were identified for recovery and recycling of lead in the LAB product lifecycle.

Concluding remarks: One can deduce the following from the analyses undertaken in this report: (1) lead recovery and recycling has been stable between 1999 and 2006; (2) lead consumption has increased at an annual rate of 2.25%, thus, the values derived in this study for opportunities dealing with lead recovery and recycling underestimate the amount of lead in scrap and waste generated; and (3) the opportunities for maximizing lead recovery and recycling are centered on spent batteries left with consumers, mishandled LAB sent to auto wreckers, slag resulting from recycling technology process inefficiencies, and lead lost in municipal waste.

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1. Introduction

The past five decades have witnessed the evolution of environmental technologies and management practices from end of pipe treatment (e.g., reactive, driven by regulations, no regard for resource consumption, limited accountability), to pollution prevention (e.g., reduce, reuse, recycle), to design for environment (e.g., proactive, beyond compliance, lifecycle analyses, ISO 14000), to most recently sustainable development (e.g., triple bottom line, multi-faceted accountability for both public and private sectors) (Mihelcic et al., 2003; Pollard et al., 2004). In today's global economy, the practice of sustainable development is of particular importance to the handling of toxic materials such as lead in order to encourage industrial organizations and its stakeholders to take an active role in maximizing human and environmental health.

The focus of this study is on lead and lead compounds as they make up the largest hazardous waste stream in the US according to the Toxic Release Inventory. We adopt an evidence-based approach to explore strategies for maximum lead recovery and recycling so as to encourage the designated US stakeholders to promote their social responsibility via sustainable development with the goal to greatly eliminate unused scrap and waste along the product lifecycle which

makes use of lead or any of its compounds. In this study, we will concentrate on the lead acid battery product as evident from statistics shown in the next section.

Currently, there is limited information on recycling rates for lead-acid batteries in the published literature. The [Battery Council International \(2005\)](#) determined that the recycling rates for recovering lead from spent LAB is approaching 99.2% for the 1999 to 2003 time period. Although very encouraging, such rates appear to be significantly higher than those reported for other countries. For example, [Bied-Charreton \(1993\)](#) documented that the recycling rate for LAB is 85% in Western Europe, (there are no other sources comparing recycling rates over the same time period). Therefore, the current state of recycling efforts in the US has been unclear so as to determine the strategies for maximum lead recovery and recycling in the face of significant demands for LAB particularly in the auto industry.

The objectives of this study are twofold: (1) to determine recycling rates for lead recovery in the LAB product lifecycle for the US market; and (2) to quantify and identify the maximum opportunities for lead recovery and recycling. The following specific aims are designed to achieve these objectives: (1) to establish the historical use of lead in the US; (2) to document the flow of lead in the LAB product lifecycle; (3) to conduct a systematic review and a critical appraisal of recycling rate calculation models for LAB lifecycle; and (4) to

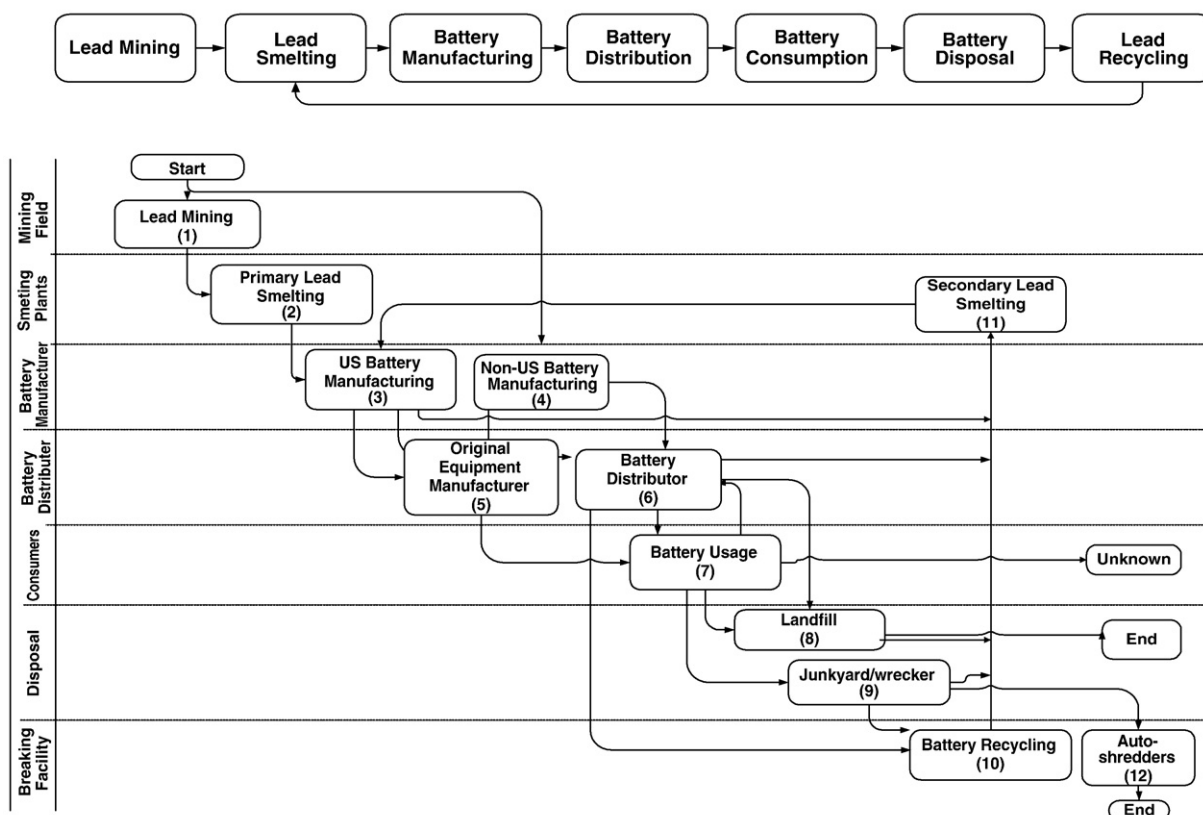


Fig. 1 – Overview of lead-acid battery product lifecycle.

quantify and to identify the maximum opportunities for lead recovery and recycling.

2. Historical use of lead in the US

According to the US Geological Survey Mineral Yearbook (Gabby, 2005), prior to 1900s lead in the US was primarily used for ammunition, brass, burial vault liners, ceramic glazes, leaded glass and crystal, paints or other protective coatings, pewter, and water lines and pipes. In the early 1900s, lead uses expanded to include bearing metals, cable covering, caulking lead, solders, and type metal. By the mid 1900s, the growth in lead use was derived from the production of public and private motorized vehicles and associated use of starting-lighting-ignition (SLI) lead-acid storage batteries and terne metal for gas tanks. In addition, the use of lead

was drawn from radiation shielding in medical analysis, video display equipment, and gasoline additive.

By the late 1900s, the use of lead was significantly reduced or eliminated in non-battery products, including gasoline, paints, solders, and water systems. As the use of lead in non-lead battery products has continued to decline, the demand of lead has continued to grow in SLI and non-SLI LAB applications (e.g., motive sources of power for industrial forklifts, mining equipment, airport ground equipment, uninterruptible power systems in telecommunication networks). In the early 2000s, the total demand for lead in all types of lead-acid storage batteries represented 88% of apparent US lead consumption. Other significant uses included ammunition (3%), oxides in glass and ceramics (3%), casting metals (2%) and sheet lead (1%). The remainder (<1%) was consumed in solders, bearing metals, brass and bronze billets, covering for cable, caulking lead, and extruded products.

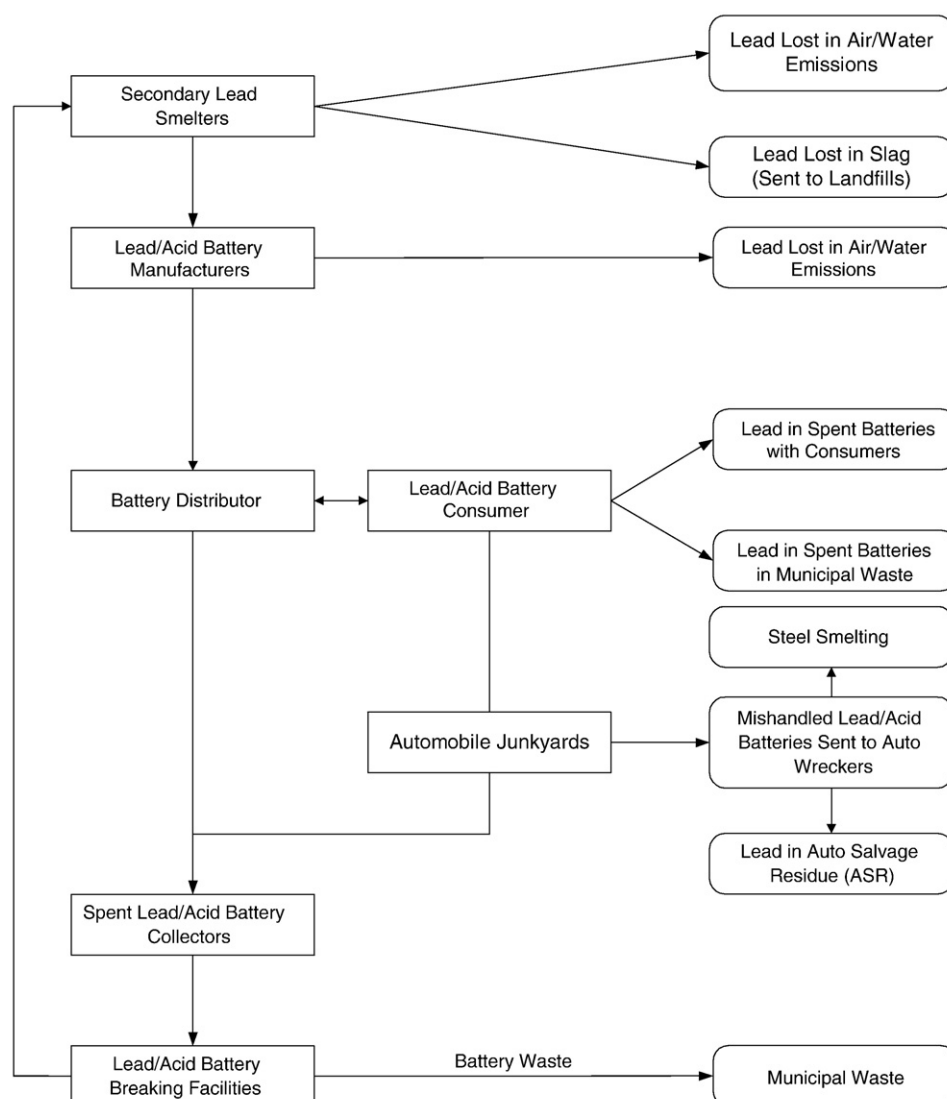


Fig. 2 – A detailed picture of lead waste arising from LAB.

3. Lead-acid battery product lifecycle

It appears that, in light of their usage of 88% of total US lead production (Gabby, 2007 Mineral Yearbook), the lead-acid batteries (LAB) product lifecycle is a natural candidate to examine for potential opportunities for lead recycling and recovery. Fig. 1 presents an overview of the product lifecycle for the manufacture of LAB. The components of this process include lead mining, lead smelting, battery manufacturing, battery distribution, battery consumption, lead disposal, and lead recycling (Wernick and Themelis, 1998; USEPA, 1998; Jolly and Rhin, 1994).

The primary lead smelting industry (box 1, in Fig. 1) produces 565,000 tons of lead, of which 78% is used in the manufacture of LAB (Gabby, 2007 Mineral Yearbook). On the other hand, secondary lead smelting (2) results in a total production of 1,130,000 tons of lead (Gabby, 2007 Mineral Yearbook), of which 93% is consumed in the manufacture of LAB (Battery Council International, 2003). As such, the ratio of lead from secondary smelting to that from primary smelting is 2.38; to put it differently, lead from secondary smelting accounts for almost 70% of the lead used in the manufacture of LAB in the US (3).

Both US and non-US (box 4, Fig. 1) battery manufacturing contribute to original equipment manufacturers (5) and battery distributors (6) which in turn satisfy the needs of US consumers (7). Consumers do not return all spent batteries to distributors. A portion of these batteries are left with consumers in which some are disposed to landfills (8) and others to automobile junkyards (9). In some occasions, spent batteries are fed to landfills from battery distributors. Battery recycling facilities (12) receive a sizable share from both battery distributors and automobile junkyards. Automobile junkyards feed upon auto wreckers (12). The feedback loop depicts that lead from spent batteries are redirected to secondary smelters from a number of sources including domestic LAB manufacturers, distributors, landfills, automobile junkyards, and recycling facilities.

A close look at the macroscopic view portrayed in Fig. 1 suggests three opportunities for lead recovery and recycling. These include: (a) lead in spent batteries with consumers, (b) mishandled batteries sent to auto wreckers, and (c) lead in spent batteries in municipal waste. Additional opportunities are shown in Fig. 2, displaying a more detailed picture. These include lead lost in air and water emissions during the process of secondary lead smelting and LAB manufacture, which are not quantified because they represent a small fraction of total

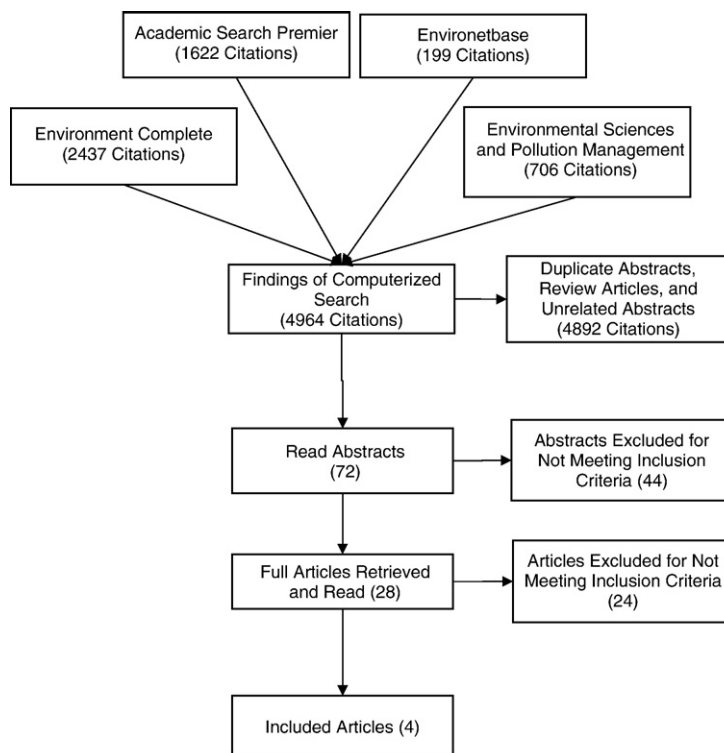


Fig. 3 – Article selection flowchart from electronic databases. Note: Sources of articles retrieved and read are: Agrawal et al., 2004; Barakat, 1998; Bied-Charreton, 1993; Cobas-Flores et al., 1996; Eriksson et al., 2003; Hansen and Lassen, 2003; Hoshimo et al., 1995; Jackson and Tansel, 1994; Kaplan and Ness, 1987; Karisson, 1999; Kleijn, 2000; Mao et al., 2006; Oliver and Rothman, 1975; Roberts, 2003; Robertson, 2001; Robertson et al., 1997; Sueishi et al., 1981; Schultmann et al., 2003; Sibley and Butterman, 1995; Smith, 1999; Spengler et al., 1997; Tietze-Stöckinger et al., 2004; Tsoulfas et al., 2002; Wernick and Themelis, 1998; Wilson, 1993; Winkler and Bilitewski, 2007.

recycling loop volume. In addition, one may observe the lead lost in slag coming out of the secondary smelting operations which depend upon the efficiency of recycling and recovery technologies.

4. Methods

4.1. Search strategy and inclusion criteria

The target area in this study is recycling rate models dedicated for lead-acid batteries. A comprehensive electronic search of databases (Academic Search Premier, Environment Complete, Environmental Sciences and Pollution Management, Environment base) was conducted with any combinations of the following keywords: recycling rate, recycling efficiency, rate calculations, rate calculation models, lead and metal recovery and recycling, waste recycling. In addition to the electronic search, research articles were identified from the list of references in review articles and bibliographies produced from the electronic search as well as general search engines such as Google. Studies published in English were only used in the study. Duplicate and unrelated abstracts as well as review articles were not included. The electronic search started on 9/30/2007 and concluded on 11/15/2007. Additional inclusion criteria were studies which were dedicated to scrap metal recycling and lead acid battery recycling.

4.2. Data/information extraction

From all included studies, we documented the following items for the description of evidence: definition of recycling rate and elements included, as well as, the model used in recycling rate calculations. The information was extracted from each article by two members of the research team independently and discrepancies in the information were resolved by consensus meetings.

4.3. Data collection, management and analysis

The identified recycling rate models from the published literature were used to calculate US rates as a function of year. A comparative assessment was made to examine the trends of recycling efforts in the US. The following data were gathered from various sources and used consistently in all models.

- Data on lead consumption by US battery manufacturers and metal recovered from used LAB by smelters was collected from the USGS Minerals Yearbook from 1995 to 2006 (Smith, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003; Gabby, 2004, 2005; Carlin et al., 2006). The Yearbook was additionally used to extract information on the amount of new scrap generated and stock changes.
- Statistics on LAB import and export was obtained from USITC (US International Trade Commission, 2008) based on Harmonized Tariff Schedule (HTS) codes, either in terms of

Table 1 – Definition of recycling rates and associated terms from different sources

Source	Recycling rate	Recycling efficiency
Bied-Charreton (1993)	Apparent recycling rate – Ratio of (real supply of scrap batteries collected to smelters and remelters in a given year) and (theoretical collection of scrap batteries available for recycling in a given year). Theoretical collection = (apparent consumption + consumption + lead content in LAB from broken vehicles)	
Sibley et al. (1995)	Recovered content of metal in recycled old scrap expressed as a percentage of apparent consumption of refined metal.	Recovered content of metal in recycled old scrap expressed as a percentage of old scrap generated.
Smith (1998)	Fraction of metal supply that is scrap on annual basis. Ratio of (consumption of old scrap + consumption of new scrap) and (apparent supply).	Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Ratio of (consumption of old scrap + exports of old scrap) and (old scrap generated + imports of old scrap + a decrease or increase in old scrap stocks).
BCI (2001, 2003, 2005)	Ratio of (total pounds of battery lead recycled) and (total pounds of battery lead available for recycling). Total pounds of battery lead recycled = total pounds of lead recycled from batteries at US secondary smelters. Total pounds of battery available for recycling = total pounds of lead in batteries consumed domestically + battery scrap lead imports – battery scrap lead exports	
Mao et al. (2006)	Ratio of (old scrap reused in year t) and (total LAB production Δt years ago). Moderate recycling rate – Ratio of (lead scrap produced in LAB manufacturing that become inputs for lead production) and (total production of batteries in same year).	

number of lead-acid batteries or kilograms of lead content. The statistics were collected for import/export of new and used LAB, imports and exports of vehicles containing batteries, and other battery types and battery parts containing lead.

- The number of vehicles sent to auto junkyards was collected from the National Automobile Dealer's Association statistics (NADA, 2007).

- The data on the amount of slag generated annually by smelters and environmental emissions due to processing were calculated from figures and statistics from various sources (Lewis and Beautement 2002; Kreusch et al., 2007).
- The amount of lead found in LAB in municipal waste was gathered from the EPA Municipal Waste Data Statistics (Materials generated in the municipal waste stream, 1960 to 2006).

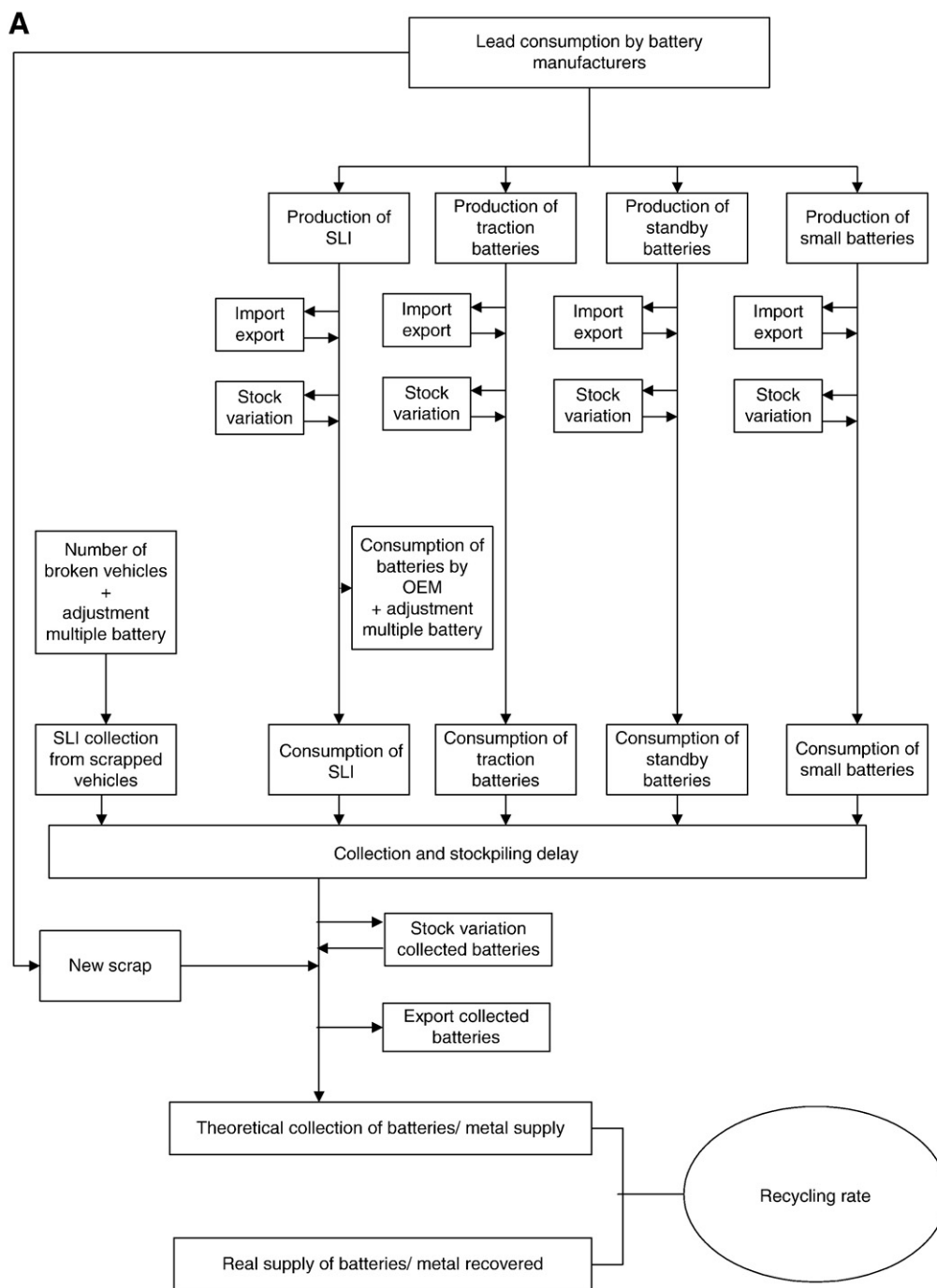


Fig. 4– A. LAB recycling rate model by Bied-Charreton (1993). B. LAB recycling rate model by Sibley et al. (1995). C. LAB recycling rate model by Smith (1998). D. LAB recycling rate model by BCI (2001, 2003, 2005). E. LAB recycling rate model by Mao et al. (2006). F. LAB recycling rate model adopted in this study. Note: Adjustment multiple battery – Adjustment made for vehicles utilizing more than one battery (e.g., trucks, heavy machinery).

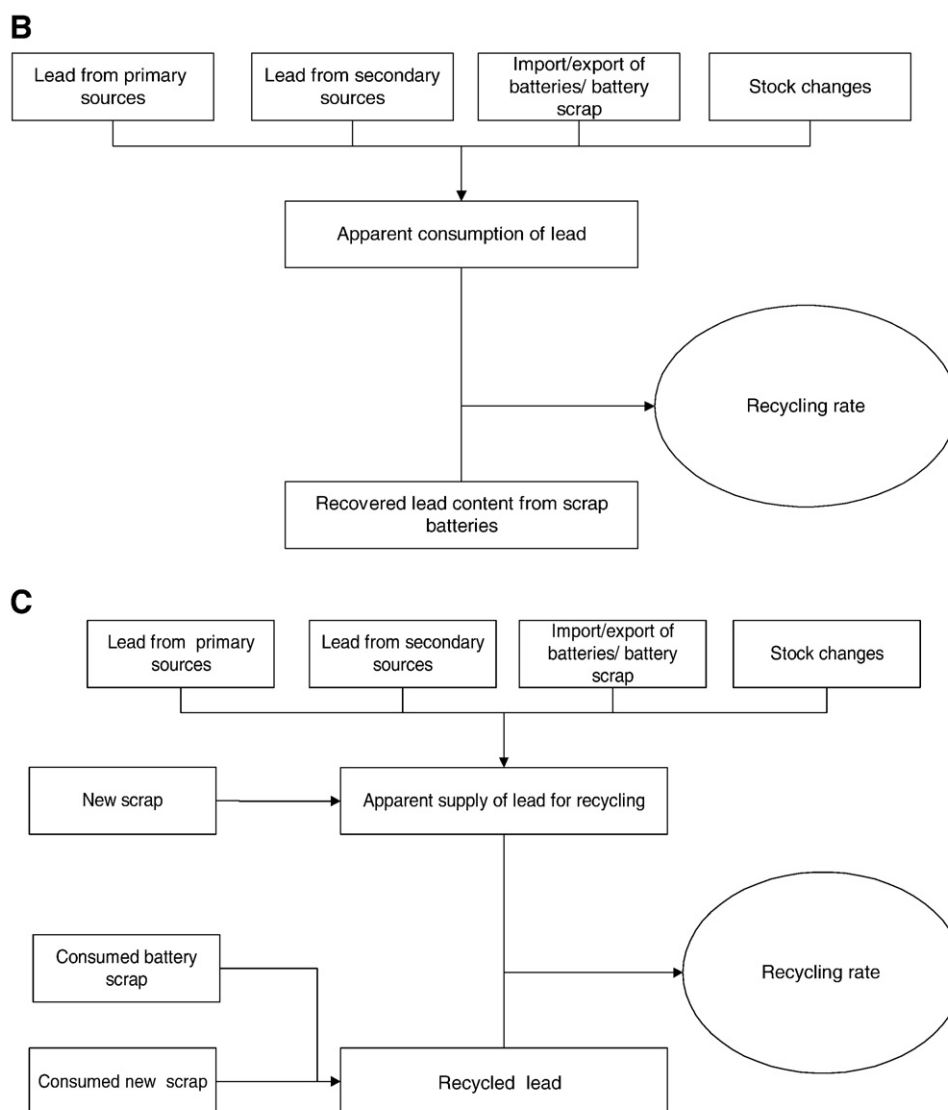


Fig. 4 (continued).

- The amount of lead found in stockpiles is obtained from the USGS Minerals Yearbook (1995–2007).

For simplicity of recycling rate calculations, it was assumed that the average useful life of lead-acid batteries is 4 years and the weight of lead content in each LAB is 10.5 kg (Smith, 1999 Mineral Yearbook).

5. Results

5.1. Identification of studies

The electronic search resulted in 4964 citations (Fig. 3). Seventy-two articles were selected after eliminating repeated abstracts, review articles and non-related topic articles. After applying the inclusion criteria, 28 articles were selected, retrieved

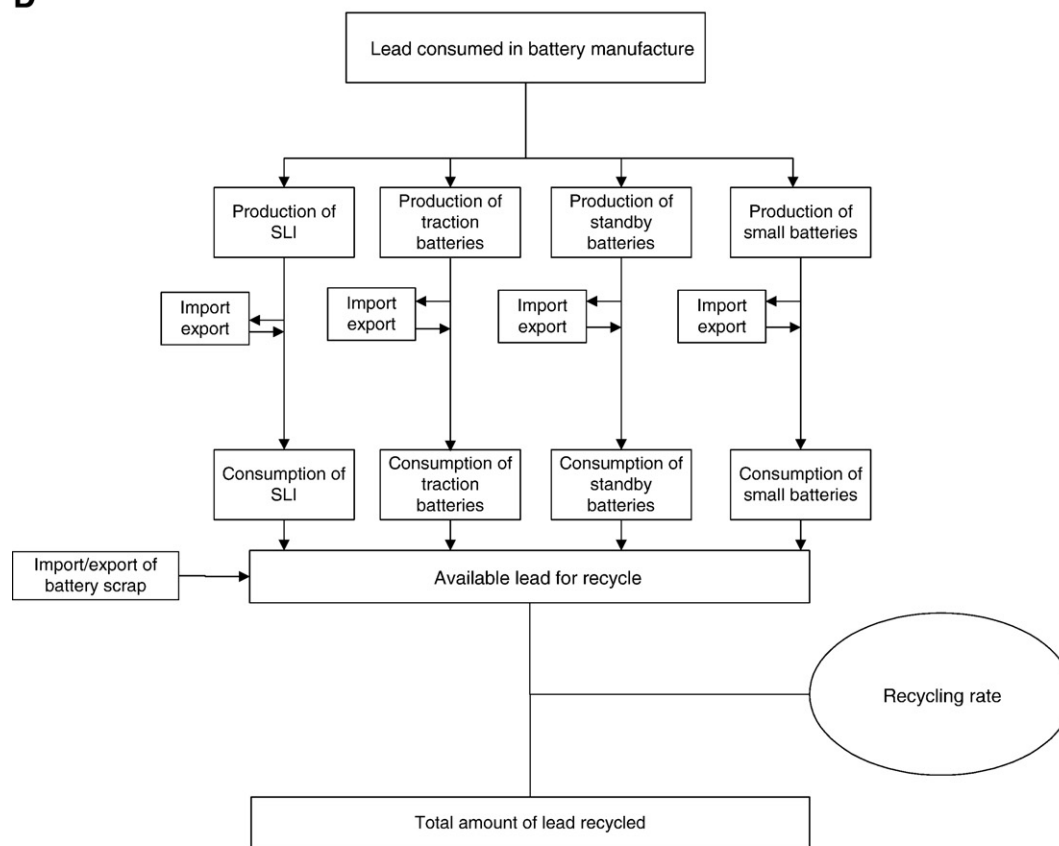
and read. Finally, four articles were chosen for inclusion into this study, namely, Bied-Charreton (1993), Sibley et al. (1995), Smith (1999), and Mao et al. (2006). Three additional reports by BCI (2001, 2003, 2005) were retrieved on the basis of bibliography search of articles and additional search of the Google database.

5.2. Description of evidence

Table 1 documents the recycling rate definitions from the articles and reports identified from the electronic search. Furthermore, Fig. 4A through e present the detailed recycling rate models for Bied-Charreton (1993), Sibley et al. (1995), Smith (1999), BCI (2001, 2003, 2005), and Mao et al. (2006), respectively. A brief description of evidence for each recycling rate model follows.

- The Bied-Charreton model (1993) consists of several steps (Fig. 4A). The first step is to calculate the theoretical quantity

D



E

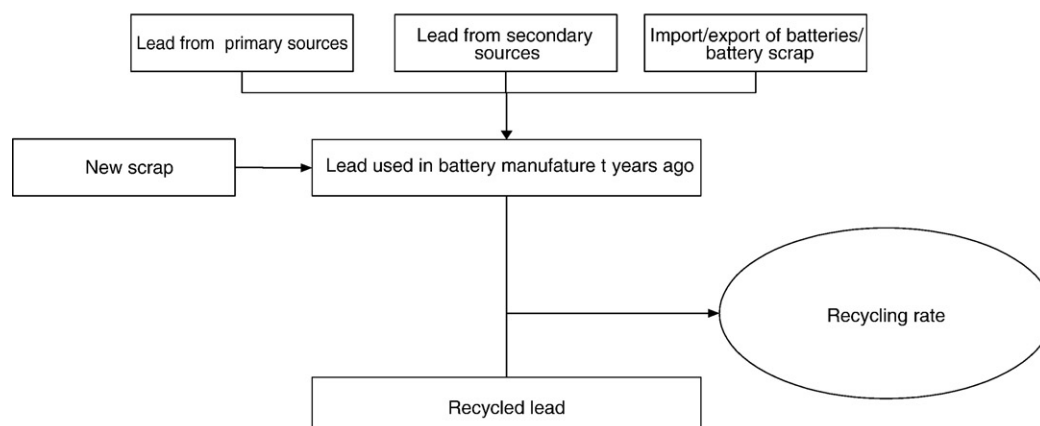


Fig. 4 (continued).

of battery scrap. For industrial and small batteries, the recycling rate calculation is based on the average service-life of each battery type and its past consumption levels. For automotive batteries (SLI), the number of scrapped batteries was made equal to the sales of replacement batteries plus those collected from scrapped vehicles; thus the amount of lead content in scrapped batteries was calculated as the product of the number of batteries and the estimated average weight per battery, 10.5 kg. Finally, the process

scrap from battery plants and the imports/exports of batteries is included to obtain the theoretical resource of battery scrap. A comparison of the theoretical value with the quantity of battery scrap delivered at lead smelters yields what is termed the apparent recycling rate because stock variations are poorly documented and the delay involved in collection and stockpiling.

- Sibley et al. (1995) have defined the recycling rate as the recovered content of metal in recycled old scrap as a

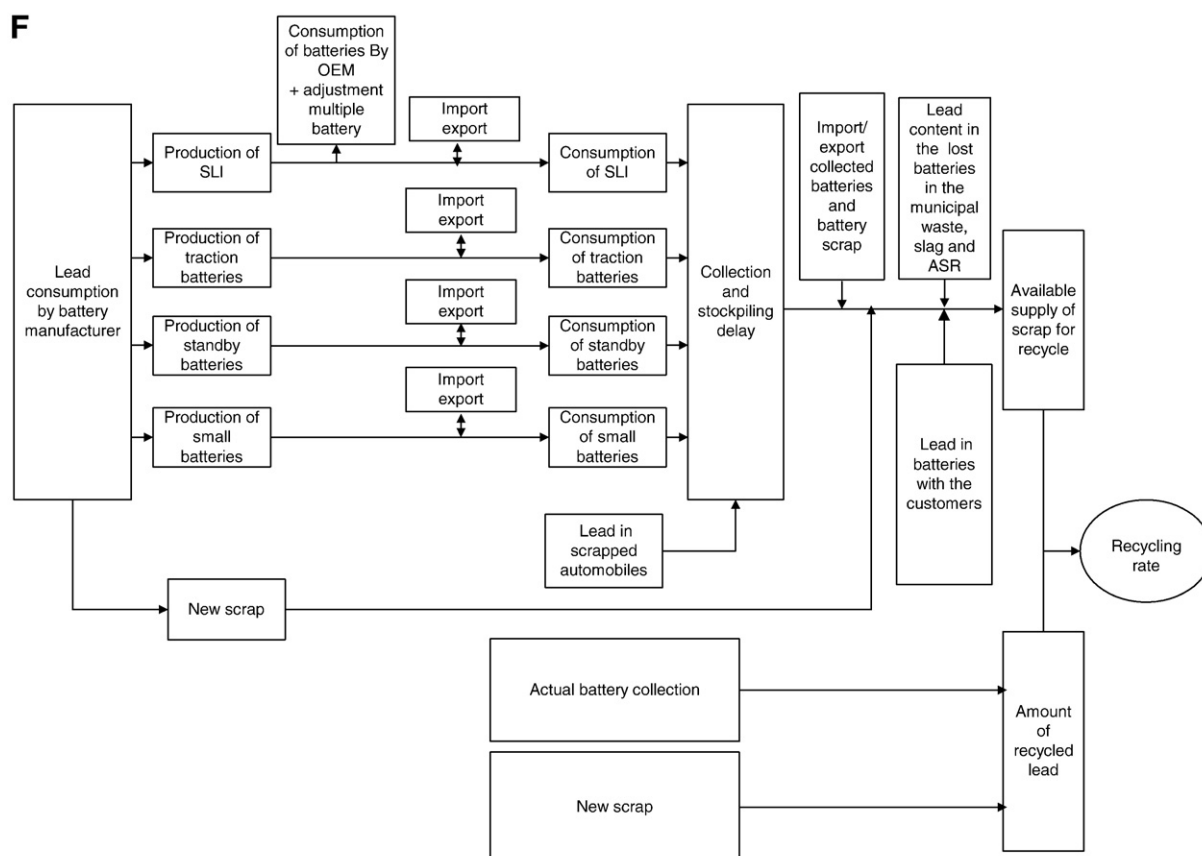


Fig. 4 (continued).

percentage of apparent consumption of refined metal, old scrap being manufactured products which have been discarded after serving its useful purpose (Fig. 4B). The apparent consumption is the refined metal used in the manufacture of products which are being discarded after their service. The Sibley's model does not consider the new scrap generated as part of available scrap for recycle. The new scrap generated in the fabrication of new products (i.e., home scrap) is assumed to be utilized efficiently.

- Smith (1999) described the recycling rate as the amount of metal recovered as a fraction of metal's apparent supply (Fig. 4C). The rate is defined on an annual basis and is the ratio between the scrap consumed that includes consumed old scrap and new scrap to the apparent supply. The apparent supply includes apparent consumption and new scrap where apparent consumption is defined in similar terms to those of Sibley et al. (1995).
- The Battery Council international (BCI 2001, 2003, 2005) defined the recycling rate as the ratio between the amounts of scrapped lead recycled to the available lead for recycle (Fig. 4D). The available lead for recycle was defined as the net lead available for recycle from domestically used batteries at the end of their useful life (both domestically manufactured and net lead from

import/export of batteries) and net import/export of lead scrap.

- Mao et al. (2006) depicted the LAB recycling rate in any given year as the ratio of old lead scrap reused in lead production in that year to the total production of lead acid batteries in t years ago, t being the useful life of batteries available for recycling (Fig. 4E). The available battery scrap for recycling includes the new primary lead (termed as resource load) and secondary lead used in the manufacture of LAB t years ago adjusted for import and export of batteries in that particular year and new scrap generated as a battery manufacturing activity.

In light of the aforementioned studies, an integrated model was developed in this study with the ultimate goal to provide quantitative assessment for the maximum opportunities for lead recovery and recycling. Fig. 4F presents such a model with an eye on these opportunities previously described in the LAB product lifecycle (see Fig. 2). None of the reviewed models took into account lead in spent batteries left with customers, lead lost in slag, and lead in spent batteries in municipal waste. On the other hand, lead in batteries found in auto junkyards and subsequently mishandled LAB sent to auto wreckers was partly considered in the Bied-Charreton study (1993) and is an essential element of the integrated model developed in this study.

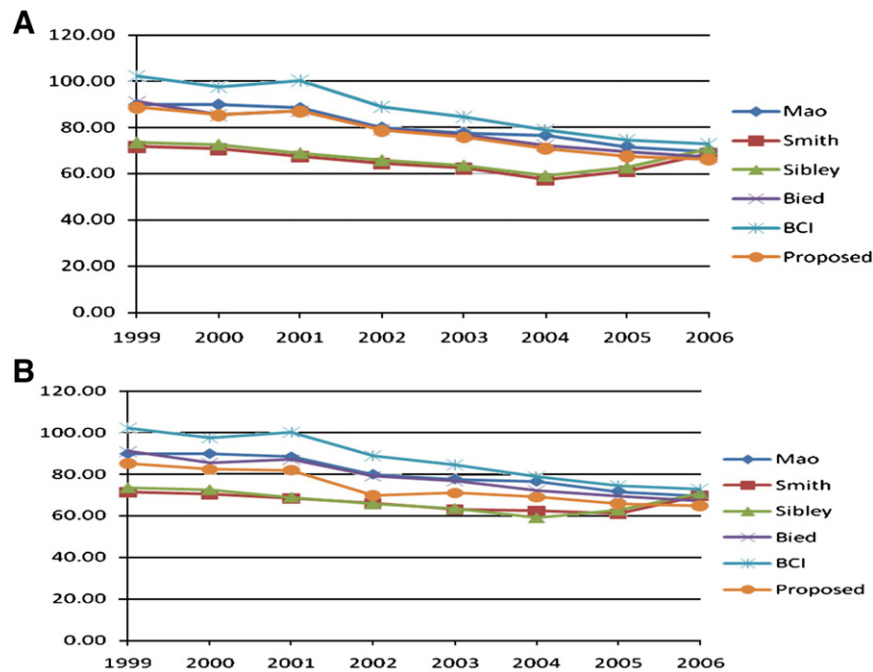


Fig. 5–A. US recycling rates for different models for the 1999 to 2006 time period. B. Revised rates for proposed model in comparison to other models.

5.3. Recycling rate calculations based on different models

The following provides mathematical expressions of the recycling rate calculated for the different models described earlier in the description of evidence.

- According to **Sibley's model (1995)**, if the amount of primary metal used in the manufacture of products is x and y is the secondary lead used, z is the net amount of lead from imported and exported batteries, and u is the net amount of lead from imported and exported scrap, then the metal consumption for the manufacture of that product would be $(x+y+z+u)$. Apparent consumption may also account for changes in industry and government stocks (say w) which have been used or replenished in that particular year in recovery process or manufacturing process. Thus, if the amount of metal recovered in any year is a , the recycling rate according to Sibley's model can be expressed as $a/(x+y+z+u+w)$.
- According to **Smith's model (1999)**, if r is the new scrap generated (i.e., home scrap) and p is the apparent consumption where $p=x+y+z+u+w$ as defined earlier in the Sibley's model, then apparent supply q is equal to $r+p$. Thus, if a is the amount of scrap recycled, the recycling rate can be expressed as $a/(r+p)$, where $p=x+y+z+u+w$.
- In the **Bied-Charreton's model (1993)**, if q is the apparent supply of lead as defined in **Smith (1998)** and n is the amount of lead available for recycle from the scrapped automobile, the theoretical supply of lead for recycle would be $m=n+q$. Finally, if a is the amount of scrapped lead collected for recycle, then,

the recycling rate is equal to $a/(n+q)$. The apparent supply in the Bied model differs from that in the Smith model as the amount of primary lead consumption (x) and secondary lead consumed (y) in battery manufacturing is calculated as the product of the number of batteries shipped by the manufacturer and the lead content per battery rather than the amount of lead consumed by the manufacturer.

- In the **BCI model (2001, 2003, 2005)**, the amount of lead from primary (x) and secondary (y) smelters is calculated differently from that by Sibley and Smith, that is, the product of domestically manufactured batteries and lead content per battery. The net lead resulting from import and export of batteries or z is calculated in a similar way; u is the net lead resulting from import and export of scrap. Thus, the lead available for recycle is expressed as $x+y+z+u$. If a is the amount of lead scrap recycled, then, the recycling rate is equal to $a/(x+y+z+u)$. BCI calculated the recycling rate over a period of 5 years as a moving average which smoothes out the variability of recycling rates over the years. For demonstration purposes, the rates have been calculated on an annual basis using this model and compared it with other models.
- In the **Mao's model (2006)**, if x , y , and z are defined as in the Sibley model, then the consumption of metal for the LAB manufacture in that particular year is $x+y+z$. If r is the new scrap generated in battery manufacturing, the lead available for recycling is p and equal to $x+y+z+r$. Finally, the recycling rate can be expressed as $a/(x+y+z+r)$.

Although the above studies provide comparable calculations of recycling rates, none of the models consider losses

due to the collection or recycling process. If we consider the definition of lead available for recycling in a conservative way, the lead content in emissions from the recycling process and the lead metal content lost as a result of mishandling (lost in municipal waste or auto salvage residue) should also be part of the available lead for recycling. Although the discussed models provide approximate recycling rates, they provide limited information on areas which could be improved to further close the lead recycling loop.

5.4. US recycling rates using different models

Appendix A provides the raw data extracted from the US Geological Society for recycling rate calculations for eight straight years spanning from 1999 to 2006. Appendix B presents step-by-step calculations of recycling rate for all models using the 2006 data. Fig. 5A shows the recycling rates for different models based on the US Geological Society data for the period of 1999 to 2006. In general, there is a downward trend for recycling rates for all models with the exception of the Sibley's and Smith's models for 2005 and 2006. This was confirmed via a simple linear regression fit for each of the six models. The following r^2 were obtained for the models: (1) Bied-Charreton (1993) – $r^2=96.5\%$; (2) Sibley et al. (1995) – $r^2=32.35\%$; (3) Smith (1999) – $r^2=35.4\%$; (4) BCI (2001, 2003, 2005) – $r^2=95.3\%$; (5) Mao et al. (2006) – $r^2=95.1\%$; (6) Current Study – $r^2=95.5\%$. As such, all models demonstrated a linear decrease as a function of time except the models by Sibley et al. (1995) and Smith (1999). Excluding the data points for 2005 and 2006, the Smith and Sibley models showed a linear pattern ($r^2=97.4\%$ and 97.9% , respectively).

An analysis of Fig. 5A suggests that the BCI model recorded the highest recycling rates, followed by Bied-Charreton and Mao, then the current study, and finally the Sibley and Smith models. These results can be explained as follows: (a) The BCI model does not account for significant scrap and waste generated in the LAB product lifecycle such as the amount of lead in spent batteries left with consumers; (b) the Bied model has higher recycling rate than the current model but lower than the BCI model because it accounts for waste due to lead in batteries of broken vehicles but not all sources of scrap and waste generated.

The recycling rates were almost the same between 1999 and 2001, then, started to decline gradually to 2006 for all models except the Smith and Sibley models. The reasons for this decline can be attributed, among other things, to one or more of the following: (a) the amount of lead recovered was virtually unchanged and fluctuating in the range of 1010 and 1060 thousand tons; (b) the amount of lead in domestic battery consumption went up from 972,300 tons in 1995 to 1,147,650 tons in 2002, that is, an 18% increase over a span of 8 years at an annual growth rate of 2.25%; (c) the amount of lead in imported batteries increased by 118%, a value much higher than the 37% recorded for lead content in exported batteries. In light of these reasons, it is possible that the recycling rates were lower than those reported for the 1999–2006 period because it was assumed that amount of lead in scrapped automobile batteries, municipal waste, spent LAB left with customers, lead content in slag from smelters, and auto salvage residue were fixed, while in reality, the

amount of scrap and waste may have gone up due to the increased domestic consumption and stagnant amount of lead recovered.

Finally, using the BCI model and industry data gathered by BCI from 1999–2003 revealed a recycling rate of 99.2%. Using BCI data, the recycling rate from the present model is 95.3%. The difference of about 4% comes from estimates of lead scrap and waste not accounted for in the BCI model. When USGS data is used, the difference between the new model and the BCI model becomes even more pronounced at 11.6%.

5.5. Strategies for lead recycling and recovery

As pointed out in the previous section, the amount of lead recovered has been stagnant in the period analyzed in this study (1999–2006). Therefore, there are ample opportunities for significantly increasing the amount of lead recovered and recycled. These opportunities include the following annual amounts of lead: (1) amount of lead in spent batteries left with consumers (140,146 tons); (2) lead lost in slag (8580 tons); (3) lead content in auto salvage residue (8573 tons); and (4) lead in municipal waste (150 tons). It should be noted that these amounts are conservative estimates particularly because lead consumption has grown at an annual rate of 2.25% from 1999 to 2006 according to the US Geological Yearbook, while these losses were assumed to be constant.

6. Discussion

It is well documented that lead is a toxic substance with significant adverse effects on human and environmental health (Finkelstein et al., 1998; Goyer, 1993, 1997; Silbergeld, 1991; Todd and Chettle, 1994). Yet, the use of lead in some industrial products such as lead-acid batteries is steadily growing to satisfy consumer demand. In light of increased lead prices, it makes economic and environmental sense to maximize lead recovery and recycling by establishing a strong ecologic interface between various stakeholders (e.g., smelters, distributors) and consumers.

Current recycling rates in the US are obtained from statistics derived from a single source, that is, the Battery Council International (BCI). The BCI reported that the recycling rates for lead content in the LAB lifecycle for the 1995 to 1999, the 1997 to 2001, and the 1999 to 2003 time periods were 93.3%, 97.1%, and 99.2%, respectively. Although these numbers are quite remarkable and demonstrate a strong recovery and recycling of lead from LAB, the values are quite high compared to figures reported in other countries. For example, Bied-Charreton (1993) reported an 85% recycling rate of LAB in Western Europe. Therefore, this exploratory investigation was undertaken to closely examine this issue using an evidence-based methodology.

A systematic review and critical appraisal was performed to evaluate the recycling rate calculation models with the goal to quantify and to identify the strategies for maximum lead recovery and recycling along the LAB product lifecycle. A comparative assessment has shown that there are marked differences between the models reviewed in this study, namely, in terms of the elements used in recycling rate calculations and

type of data used in the calculations. Subsequently, an integrated model was developed in this study on the basis of the identified elements in the LAB product lifecycle and those reported in the reviewed models. In addition, we relied on the amount of lead, as advocated by BCI and others such as Bied-Charreton (1993), calculated as the number of domestically consumed batteries multiplied by the amount of lead content per battery. These calculations produced more realistic estimates than the total amount of lead consumed and reported for the LAB manufacturers. A similar approach was used for the calculations of lead in other elements.

The results obtained in this study showed that recycling rates were declining for the 1999 to 2006 time period. This was attributed to a numbers of reasons, including, (1) amount of lead recovered was stagnant, (2) consumption of lead was growing at a 2.25% annual rate, and (3) amount of lead in imported batteries increase at a higher rate than that for exported batteries. In light of the aforementioned, the results of this study confirmed the need to explore opportunities for lead recovery and recycling along the path of the LAB lifecycle. A possible explanation for the stagnation of lead recovery from spent batteries in the US (1999–2006) is that the number of secondary smelters dropped from 42 companies operating 50 plants in 1995 (USEPA, 1995) to 15 companies operating an estimated number of 21 plants in 2006 (Carlin et al., 2006) possibly due to strict environmental regulations requiring a number of effective and sometimes costly environment safeguards in place to achieve compliance (Hilson, 2000). Fewer facilities may have the effect of reducing the number of recycling channels available to capture lead scrap. Conversely, consolidating lead production may also have the effect of making production more efficient via economies of scale and more focused regulatory scrutiny from regulatory agencies.

Our findings suggest that the opportunities are centered on the following: (1) lead content in spent batteries with consumers (140,146 tons/year), (2) mishandled LAB sent to auto salvage residue (8573 tons/year), (3) slag generated due to the inefficiencies of lead recycling technologies (8580 tons/year), and (4) lead lost in municipal waste (150 tons/year). Without accounting for these opportunities, the recycling rate using the proposed model approaches 87.59%, a value that is very close to the 87.41% recycling rate calculated for the BCI model for the 1999 to 2006 time period. However, accounting for these opportunities, the recycling rate for the proposed model is estimated at 77.4% which is about 10% less than that for the BCI model. The question becomes: where does the 13% of unaccounted for lead go to in the product lifecycle, i.e. the difference between 100% recycling and the 87% recycling rate that discounts the identified opportunities? A possible answer is that the amount of lead estimated in the proposed model is significantly underestimated. For example, consider the amount of lead lost in municipal waste. It was estimated conservatively at 0.1% of the discarded LAB reported in the USEPA (2006). In light of the recycling rate comparison above, perhaps this estimate should be higher. Regardless, it is evident that there are significant amounts of lead unaccounted for in the product lifecycle.

A close reexamination of the EPA reports for the 1999 to 2006, we used the actual amounts of lead recovered from LAB

in municipal waste (there are discrepancies in these reports about the actual amounts of lead recovered). In light of these numbers as well as varying the amounts of lead in other types of waste from year to year, the recycling rates were recalculated for the proposed model and were compared to those generated from other models.

Fig. 5B shows the revised recycling rates according to the proposed model. It is shown that the recycling rates derived from the proposed model are around or above 80% from 1999 to 2001 in comparison to the 97.5%+ rates calculated by the BCI model. Thereafter, recycling rates were dropped by more than 10%. As such, one can deduce that these opportunities should be closely reexamined with different stakeholders to confirm the amounts of lead available for recovery and recycling along the product lifecycle. Furthermore, one should expand the period of examination to perhaps from 1990 to the present subject to data availability and calculations.

7. Concluding remarks

The following observations can be derived in light of the data collected for the 1999–2006 period:

1. Lead recovery and recycling has been stagnant at steady values in the US for the 1999 to 2006 time period. Therefore, significant efforts should be undertaken to stimulate and improve recycling efforts in the US. In this regard, a major partnership with stakeholders in the LAB product lifecycle is essential.
2. Lead consumption has gone up at an annual growth rate of 2.25%. Therefore, it is expected that the conservative values derived in this study for opportunities for metal recovery and recycling underestimate the amount of lead in scrap and waste generated.
3. The opportunities for maximizing lead recovery and recycling are centered on the spent batteries left with consumers, mishandled LAB sent to auto wreckers, slag resulting from recycling technology process inefficiencies, and lead lost in municipal waste. High lead prices should provide increased incentive to reduce the lead lost to auto wreckers and improve smelter efficiencies. Spent batteries with consumers and lead lost to landfills may offer most fruitful opportunities since consumers are less cognizant of lead prices, i.e. less likely to incorporate into their decision making, at the end of a product's useful life.

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Appendix A. Raw data extracted from various sources for the recycling rate calculations

Description	year											
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Lead consumption by US battery manufacturers ^a	1,360,000	1,340,000	1,390,000	1,430,000	1,470,000	1,490,000	1,390,000	1,190,000	1,170,000	1,290,000	1,290,000	1,400,000
Battery lead recovered ^a	867,000	992,000	991,000	1,010,000	1,020,000	1,020,000	1,000,000	1,010,000	1,060,000	1,040,000	1,050,000	1,060,000
New lead based scrap generated ^a	38,600	36,600	54,000	45,800	42,700	35,500	47,300	34,800	33,900	12,500	14,200	13,500
Domestic battery consumption in millions of units ^b	92.6	93.4	89.4	98.5	100.5	99.5	106.9	109.3				
Lead in domestic battery consumption ^c	972,300	980,700	938,700	1,034,250	1,055,250	1,044,750	1,122,450	1,147,650				
Import battery lead ^d	240,366	257,416	295,386	330,373	416,311	447,162	483,303	524,272				
Export battery lead ^d	119,026	137,638	149,435	135,479	139,911	143,865	155,871	162,738				
Import lead scrap ^e					32,177	27,839	28,540	21,036	20,735	30,478	29,958	69,785
Export lead scrap ^e					127,117	82,144	113,318	112,004	99,154	60,832	72,084	123,416
Number of scrapped automobiles ^f					11,663,602	14,298,759	14,121,720	13,295,749	12,084,680	11,903,293	9,988,864	12,007,700
Lead content in scrapped automobile batteries ^g					122,468	150,137	148,278	139,605	126,889	124,985	104,883	126,081
Lead in spent batteries with consumers ^h	140,146	140,146	140,146	140,146	140,146	140,146	140,146	140,146	140,146	140,146	140,146	140,146
Lead found in municipal waste ⁱ					150	150	150	150	150	150	150	150
Lead content in auto salvage residue ^j					8573	8573	8573	8573	8573	8573	8573	8573
Lead content in slag from smelters ^k					8580	8580	8580	8580	8580	8580	8580	8580
Stock changes ^l	54,400	54,400	54,400	54,400	54,400	54,400	54,400	54,400	54,400	54,400	54,400	54,400

^a US Geological Survey Minerals Yearbook (1995–2006).

^b US domestic battery shipments extracted from [Battery Council International \(2007\)](#).

^c Calculated using number of battery consumption multiplied by 10.5 kg lead/battery.

^d Data extracted from the [United States International Trade Commission \(2008\)](#) as the number of batteries or vehicles. The number was calculated as the net of imported and exported batteries multiplied by 10.5 kg lead/battery.

^e The data gathered from the United States International Trade Commission was mixed. Some data was reported as number of batteries or vehicles (subsequently amount of lead is calculated as explained previously); other data was documented in total amount of lead.

^f Data extracted from the [National Automobiles Dealer Association \(2007\)](#).

^g Calculated using number of scrapped automobile batteries multiplied by 10.5 kg lead/battery.

^h There are no ready numbers to be used for this category; therefore, a procedure was devised for this purpose. First, the lower and upper limits of the variability range were established from the literature (lower limit was extracted from the [2005 AAA Exchange](#) – 105 M lb of lead was obtained for 2005 and it was assumed to be constant for all years. The upper limit was obtained from the BCI Response to the [2003 Environmental Defense](#) report “Getting the Lead Out” and corresponds to 20% of the number of American households ([US Department of Commerce](#)) for 2001 (312,217,502) or 2003 (318,639,922)). For 2003, the amount of lead was estimated at (318,639,922*0.2*21 lb) and was assumed constant for all examined years. Second, a positively skewed distribution was assumed to be conservative towards the lower end. The expected value was calculated as (range/4), that is, ((1,338,287,672 – 105,000,000)/4)/2200 or 140,146 tons. It should be noted that although the above number was assumed to be constant year-in and year-out in this exploratory study, accumulation may go up due to the growing use of LAB in the US market. Upon availability of more data, future research will take this issue into account.

ⁱ Estimated at 0.1% of discarded batteries in the EPA Report on Municipal Waste Stream 2006. In the EPA report, 150,000 tons was reported for 2002 (peak value in reported period). The calculated value in Table A1 was estimated at 0.1% of the 150,000 tons and was assumed to be the same for all examined years.

^j Calculated from a letter sent by the UM Ecology Center to EPA 2005. It is estimated in a similar way to the above calculations in footnote h, that is, ((36,000 – 1710)/4) or 8573 tons. The upper limit was quantified as 12,000 mg/kg*3,000,000 tons/1,000,000; the lower limit was estimated as 570 mg/kg*3,000,000 tons/1,000,000. It should be noted that lead content in ASR typically includes lead coming from different auto components such as LAB and wheel weights. We have assumed a value that is slightly higher than the lower limit because the percent of lead content in LAB is relatively higher than that in other auto components. AS such, this value is conservative and does not overestimate the lead content in ASR coming from LAB.

^k The values were obtained from [Kreusch et al. \(2007\)](#). The annual amount of lead content in slag was calculated as: (300 kg of slag/ton of refined lead recovered)*(2.77 mass% of lead)*amount of lead recovered in a year (average of lead recovered from 1999 to 2006)=8580 tons.

^l The data was extracted from the USGS Minerals Yearbook (1995–2007).

Appendix B. Comparison of all models using 2006 data for recycling rate calculations

Description	Bied-Charreton	Sibley	Smith	BCI	Mao	Proposed Model
Battery lead recovered (X1)	1,060,000	1,060,000	1,060,000	1,060,000	1,060,000	1,060,000
New lead based scrap generated (X2)			13,500			13,500
Numerator X	X = X1	X = X1	X = X1 + X2	X = X1	X = X1	X = X1 + X2
Total X	1,060,000	1,060,000	1,073,500	1,060,000	1,060,000	1,073,500
Lead consumption by US battery manufacturers (Y1)		1,190,000	1,190,000			
Lead in domestic battery consumption in 2002 (Y2)	1,147,650			1,147,650	1,147,650	1,147,650
Import battery lead in 2002 (Y3)	524,272	524,272	524,272	524,272	524,272	524,272
Export battery lead in 2002 (Y4)	162,738	162,738	162,738	162,738	162,738	162,738
Import lead scrap in 2006 (Y5)	69,785	69,785	69,785	69,785		69,785
Export lead scrap in 2006 (Y6)	123,416	123,416	123,416	123,416		123,416
Lead content in scrapped automobile batteries (Y7)	126,081					
New lead based scrap generated (Y8)			13,500		13,500	13,500
Lead found in municipal waste (Y9)						150
Lead content in auto salvage residue (Y10)						8573
Lead content in slag from smelters (Y11)						8580
Stock changes (Y12)			54,400			
Lead in spent batteries with consumers (Y13)						140,146
Denominator Y	Y = Y2 + Y3 – Y4 + Y5 – Y6 + Y7	Y = Y1 + Y3 – Y4 + Y5 – Y6	Y = Y1 + Y3 – Y4 + Y5 – Y6 + Y8 + Y12	Y = Y2 + Y3 – Y4 + Y5 – Y6	Y = Y2 + Y3 – Y4 + Y8	Y = Y2 + Y3 – Y4 + Y5 – Y6 + Y8 + Y9 + Y10 + Y11 + Y13
Total Y	1,581,633	1,497,903	1,565,803	1,455,553	1,522,684	1,626,505
Recycling rate=	67.02	70.77	68.56	72.82	69.61	66.00

REFERENCES

- Agrawal A, Sahu KK, Pandey BD. Recent trends and current practices for secondary processing of zinc and lead. Part I: lead recovery from secondary sources. *Waste Manag Resour* 2004;22:240–7.
- AAA Exchange. Battery roundup fact sheet. <http://www.aaapublicaffairs.com/Main/Default.asp?CategoryID=8&SubCategoryID=28&ContentID=82&SubContentID=93> 2005 accessed on 10/15/2007.
- Barakat MA. Recovery of lead, tin and indium from alloy wire Scrap. *Hydrometallurgy* 1998;49:63–73.
- BCI (Battery Council International). National recycling rate study; 2001. Chicago, Illinois.
- BCI (Battery Council International). National recycling rate study; 2003. Chicago, Illinois.
- BCI (Battery Council International). National recycling rate study; 2005. Chicago, Illinois.
- BCI (Battery Council International). Breakdown of US domestic battery shipments 1937–2006; 2007.
- Battery Council International. Response to: 'Getting the lead out: impacts of and alternatives for automotive lead uses'; 2005.
- Bernardes AM, Espinosa DCR, Tenório JAS. Recycling of batteries: a review of current processes and technologies. *J Power Sources* 2004;130:291–8.
- Bied-Charreton B. Closed loop recycling of lead/acid batteries. *J Power Sources* 1993;42:331–4.
- U.S. Department of Commerce. Bureau of the census current population reports: projections of the number of households and families in the United States: 1995 to 2010. <http://www.census.gov/prod/1/pop/p25-1129.pdf>. accessed on 15/10/2008.
- Carlin JF, Smith GR, Bi X. Lead: US. Geological Survey Minerals Yearbook. United States Geological survey; 2006. p. 42.1–42.22.
- Cobas-Flores E, Hendrickson CT, Lave LB, McMichae FC. Life cycle analysis of batteries using economic input-output analysis. *IEEE* 1996:130–4.
- Environmental Defense, Ecology Centre. Getting the lead out: Impacts of and alternatives for automobile lead uses. Washington DC; 2003.
- Eriksson O, Olofsson M, Ekvall T. How model-based systems analysis can be improved for waste management planning. *Waste Manag Res* 2003;21:488–500.
- Finkelstein Y, Markowitz ME, Rosen JF. Low-level lead-induced neurotoxicity in children: an update on central nervous system effects. *Brain Res Rev* 1998(27):168–76.
- Gabby PN. Lead: US. Geological Survey Minerals Yearbook. United States Geological Survey; 2004. p. 43.1–43.19.
- Gabby PN. Lead: US. Geological Survey Minerals Yearbook. United States Geological Survey; 2005. p. 43.1–43.20.
- Goyer RA. Toxic and essential metal interactions. *Ann Rev Nutr* 1997;17:37–50.
- Goyer RA. Lead toxicity: current concerns. *Environ Health Perspect* 1993;100:177–87.
- Hansen E, Lassen C. Experience with the use of substance flow analysis in Denmark. *J Ind Ecol* 2003;6(3/4):201–19.
- Heijungs R, Guine'e JB. Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. *Waste Manag* 2007;27:997–1005.
- Hilson G. Barriers to implementing cleaner technologies and cleaner production (CP) practices in the mining industry: a case study of the Americas. *Min Eng* 2000;13(7):699–717.
- Hoshino T, Yura K, Hitomi K. Optimization analysis for recycle-oriented manufacturing systems. *Int J Prod Res* 1995;33(8):2069–78.
- Jackson H, Tansel B. Recycling analysis of lead acid batteries. *J Resour Manag Technol* 1994;22(2):96–9.
- Jolly R, Rhin C. The recycling of lead-acid batteries: production of lead and polypropylene. *Resour, Conserv Recycl* 1994;10:137–43.
- Kaplan RS, Ness H. Recycling of metals. *Conserv Recycl* 1987;10(1):1–13.
- Karlsson S. Closing the technospheric flows of toxic metals: modeling lead losses from a lead-acid battery system for Sweden. *J Ind Ecol* 1999;3(1):23–40.
- Kleijn R. In = out the trivial central paradigm of MFA? *J Ind Ecol* 2000;3(2/3):8–10.
- Kreusch MA, Ponte MJJS, Ponte HA, Kaminari NMS, Marino CEB, Mymrin V. Technological improvements in automobile battery recycling. *Res, Conserv Recycl* 2007;52:368–80.
- Lewis AE, Beautement C. Prioritizing objectives for waste reprocessing: a case study in secondary lead refining. *Waste Manag* 2002;22:677–85.
- Mao J, Lu Z, Yang Z. The eco-efficiency of lead in China's lead-acid battery system. *J Ind Ecol* 2006;10(1/2):185–97.
- Mihelcic JR, Crittenden JC, Small MJ, David R, Shonnard RR, Hokanson DR, Zhang Q, Huichen Sorby S, James V, John W, Sutherland JW, Schnoor JL. Sustainability science and engineering: the emergence of a new metadiscipline. *Environ Sci Technol* 2003;37:5314–24.
- NADA (National Automobile Dealers Association) data. Vehicles in Operation and Scrappage. National Automobile Dealers Association. McLean, Virginia. http://www.nada.org/NR/rdonlyres/233DD641-C551-479A-8669-5D7E877A5B92/0/NADA_DATA_2007.pdf 2007 accessed on 15/10/2007.
- Oliver AN, Rothman H. The value of recycling: a framework for analysis. *Ind Mark Manage* 1975;4:133–41.
- Pollard SJT, Brookes A, Earl N, Lowe J, Kearney T, Nathanail CP. Integrating decision tools for the sustainable management of land contamination. *Sci Total Environ* June 5, 2004;325(1–3):15–28.
- Roberts H. Changing patterns in global lead supply and demand. *J Power Sour* 2003;116:23–31.
- Robertson JGS. MIM primary lead production: a life-cycle approach to identification and management of the environmental effects. Professional paper. *Inst Min Metall* 2001:C33–42.
- Robertson JGS, Wood JR, Ralph B, Fenn R. Analysis of lead/acid battery life cycle factors: their impact on society and the lead industry. *J Power Sour* 1997;67:225–36.
- Sueishi T, Morioka T, Ueta K. The use of secondary lead for resource, energy and environmental conservation. *Conserv Recycl* 1981;4(3):177–84.
- Schultmann F, Engels B, Rentz O. Closed-loop supply chains for spent batteries. *Interfaces* 2003;33(6):57–71.
- Sibley SF, Butterman WC. Staff. Metals recycling in the United States. *Resour, Conserv Recycl* 1995;15:259–67.
- Silbergeld EK. Lead in bone: implications for toxicology during pregnancy and lactation. *Environ Health Perspect* 1991;91:63–70.
- Smith GR. Lead recycling in the United States in 1998. Flow studies for recycling metal commodities in the United States. United States Geological Survey; 1999.
- Smith GR. Lead: U.S. Geological Survey — Minerals Information. United States Geological Survey; 1995. p. 1–20.
- Smith GR. Lead: U.S. Geological Survey — Minerals Information. United States Geological Survey; 1996. p. 1–22.
- Smith GR. Lead: U.S. Geological Survey — Minerals Information. United States Geological Survey; 1997. p. 44.1–44.22.
- Smith GR. Lead: U.S. Geological Survey — Minerals Information. United States Geological Survey; 1998. p. 44.1–44.24.
- Smith GR. Lead: U.S. Geological Survey — Minerals Information. United States Geological Survey; 1999. p. 44.1–44.23.
- Smith GR. Lead: U.S. Geological Survey Minerals Yearbook. United States Geological Survey; 2000. p. 45.1–45.20.
- Smith GR. Lead: U.S. Geological Survey Minerals Yearbook. United States Geological Survey; 2001. p. 44.1–44.23.
- Smith GR. Lead: U.S. Geological survey Minerals Yearbook. United States Geological Survey; 2002. p. 44.1–44.23.
- Smith GR. Lead: U.S. Geological Survey Minerals Yearbook. United States Geological Survey; 2003. p. 43.1–43.20.
- Spengler T, Puchert H, Penkuhn T, Rentz O. Environmental integrated production and recycling management. *Eur J Oper Res* 1997;97:308–26.

- Tietze-Stöckinger I, Fichtner W, Rentz O. A model to minimize joint total costs for industrial waste producers and waste management companies. *Waste Manag Res* 2004;22:466–76.
- Todd AC, Chettle DR. In vivo X-ray fluorescence of lead in bone: review and current issues. *Environ Health Perspect* 1994;102:172–8.
- Tsoufas GT, Pappis CP, Minner S. An environmental analysis of the reverse supply chain of SLI batteries. *Resour, Conserv Recycl* 2002;36:135–54.
- USEPA (United States Environmental Protection Agency). Materials generated in the municipal waste stream, 1960 to 2006. <http://www.epa.gov/epaoswer/non-hw/muncpl/pubs/06data.pdf> accessed on 15/1/2008.
- USEPA (United States Environmental Protection Agency). AP 42, fifth edition, compilation of air pollutant emission factors, Volume 1: stationary point and area sources; 1995.
- USEPA (United States Environmental Protection Agency). Locating and estimating air emissions from sources of lead and lead compounds 1998. Office of Air Quality Planning and Standards. Research Triangle Park, NC 27711.
- (United States International Trade Commission) USITC. Interactive tariff and trade dataweb: U.S. International Trade Commission. <http://dataweb.usitc.gov> accessed on 5/2/2008.
- Wernick IK, Themelis NJ. Recycling metals for the environment. *Ann Rev- Energy Environ* 1998;23:465–97.
- Wilson DN. New approaches to the collection of scrap batteries. *J Power Sour* 1993;42:319–29.
- Winkler J, Bilitewski B. Comparative evaluation of life cycle assessment models for solid waste management. *Waste Manag* 2007;27:1021–31.